

**Ultrahigh energy neutrino scattering onto relic light
neutrinos in galactic halo as a possible source
of highest energy extragalactic cosmic rays**

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ABSTRACT

The diffuse relic neutrinos with light mass are transparent to Ultrahigh energy (UHE) neutrinos at thousands EeV, born by photoproduction of pions by UHE protons on relic 2.73 K BBR radiation and originated in AGNs at cosmic distances. However these UHE ν s may interact with those (mainly heaviest ν_{μ_r} , ν_{τ_r} and respective antineutrinos) clustered into HDM galactic halos. UHE photons or protons, secondaries of $\nu\nu_r$ scattering, might be the final observed signature of such high-energy chain reactions and may be responsible of the highest extragalactic cosmic-ray (CR) events. The chain-reactions conversion efficiency, ramifications and energetics are considered for the October 1991 CR event at 320 EeV observed by the Fly's Eye detector in Utah. These quantities seem compatible with the distance, direction and power (observed at MeV gamma energies) of the Seyfert galaxy MCG 8-11-11. The $\nu\nu_r$ interaction probability is favoured by at least three order of magnitude with respect to a direct ν scattering onto the Earth atmosphere. Therefore, it may better explain the extragalactic origin of the puzzling 320 EeV event, while offering indirect evidence of a hot dark galactic halo of light (*i.e.*, $m_\nu \sim$ tens eV) neutrinos, probably of tau flavour.

1. Introduction

The highest energy CR, with $E > 10^{19}$ eV, (excluding neutrinos) are severely bounded to nearby cosmic distances by the opacity of the 2.73 K BBR (GZK cutoff) (Greisen 1966; Zat'sepin, Kuz'min 1966; Gould, Schreder 1966) as well as by the extragalactic radiobackground opacity (Clark, Brown, Alexander 1970; Protheroe, Biermann 1996). The Inverse Compton Scattering ($e^\pm \gamma_{BBR} \rightarrow e^\pm \gamma$, $p\gamma_{BBR} \rightarrow p\gamma$, (Longair 1994; Fargion, Konoplich, Salis 1997)), the photopair production at higher energies ($p\gamma_{BBR} \rightarrow pe^+e^-$, $\gamma\gamma_{BBR} \rightarrow e^+e^-$) and, most importantly, the photoproduction of pions ($p\gamma_{BBR} \rightarrow p + N\pi$, $n\gamma_{BBR} \rightarrow n + N\pi, \dots$) (Longair 1994) constrain a hundred-EeV CR to few Mpc for the characteristic pathlengths of either charged CR (protons, nuclei), as well as neutrons and photons. The most energetic CR event of 320 EeV, at the Utah Fly's Eye detector, keeps the primeval source direction within few degrees, even if it was a charged one, because of its high magnetic rigidity (Bird et al. 1994). However, no nearby (< 60 Mpc) source candidate (AGN, QSO) has been found up to now in the arrival direction error box. Therefore, presently, there is no reasonable explanation for the 320 EeV event, in case its origin is extragalactic. An alternative solution to this puzzle, based on an extraordinary extragalactic magnetic field (whose coherence length, ranging the largest astrophysical distances, might be able to bend the CR trajectory from off-axis nearby potential sources, like M82 and Virgo A (Elbert, Sommers 1995)) is improbable (Medina-Tanco 1997). A *local* (galactic halo) origin of the cosmic ray, is unpopular because of the lack of known processes able to accelerate cosmic rays in small galactic objects as SN remnants or jets up to such high energies. Direct cosmic neutrinos reaching the Earth atmosphere, while able to reach the Earth from any cosmological distance, are unable to produce the observed shower of the 320 EeV event (Elbert, Sommers 1995). Exotic sources of the EeV CR as monopole decay or topological defect annihilation have also been considered (Elbert, Sommers 1995). However such models do not provide any detailed prediction (no one knows

the primordial monopoles density) and they seem just *a posteriori, ad hoc* solutions. Here we want to address a more conventional solution based on the widely accepted assumption that neutrinos have a light mass and therefore they could cluster into large galactic halos, where they play an important role as *hot dark matter*. Their number density, cross sections and halo sizes are large enough to produce, by $\nu\nu$ electroweak W^\pm/Z bosons exchange, secondaries inside the galactic halo, mainly photons by π^0 decay and protons, which could be the source of the observed 320 EeV event (Fargion, Salis 1997).

2. Relic neutrino clustering

Let us consider the UHE ν scattering onto light relic ν 's in the galactic halo. In principle, any neutrino flavor may be involved either as a source or as a target for the present process. Let us label by ν the hitting high-energy neutrino and by ν_r the target relic one. UHE electronic neutrinos may derive from neutron decay in flight, or at lower energies from muon decay. Muonic neutrinos may be born as secondary in pion decay. Tau neutrinos may occur if the primary cosmic rays are generated in hadronic interactions (Dar, Laor 1996) or if some neutrino flavor mixing occurs (Fargion 1997). The target neutrinos, relic of early Universe, are clustered around the galactic halo. All the neutrino flavours are born at nearly the same cosmic homogeneous BBR density $n_\nu \sim (4/11)n_\gamma$. Neutrinos with a light mass (few or tens eV) must condense around the galactic halos because of their earliest decoupling from thermal equilibrium, and because of the mutual barion-neutrino multifluid gravitational clustering during the galaxy formation (Zel'dovich 1980; Fargion 1983). Because of the neutrino mass role in defining the early Jeans instability, the free streaming mass and the halo size, the heavier (tau or mu) neutrino halos are expected to be more clustered and dense than a lighter (electronic) halo.

Let us review in more detail the role and the origin of such HDM neutrinos in galactic halos

and their role in the interaction with the UHE neutrinos. In the early Universe, the thermal equilibrium provides the most efficient source of the present neutrino density, whose relic number may be easily derived by entropy conservation. The MeV neutrino relics decouple from the thermal bath of photons during the first second of the Universe life, as soon as electron pairs (which play the role of catalizers for the neutrino equilibrium) annihilate, and heat the relic photons temperature by an extra factor $(11/4)^{1/3}$ with respect to the neutrino one. The cosmological neutrino density, for each flavor and state, stems directly from the previous factor and becomes $n_\nu = (4/11)n_\gamma \simeq 108 \text{ cm}^{-3}$. Charged currents keep the electronic neutrinos in thermal equilibrium, while the muonic and tauonic ones are kept in equilibrium by the slightly less efficient neutral currents. The cosmic expansion *cools* the ultrarelativistic neutrino and, as soon as it reaches the non-relativistic regime $\kappa_B T_\nu \simeq m_\nu c^2$, allows the collisionless neutrino fluid to grow its density contrast (Fargion 1983). The barion density perturbations are meanwhile smeared out by photons up to the Silk size and mass, at a later recombination epoch ($z \sim 1500$). Once the barions decouple from radiation, their density contrast $\delta \rho_B / \rho_B$ may grow around the primordial neutrino gravitational seeds. Moreover, the barions may dissipate (by radiation) their gravitational energy, leading to faster non-linear gravitational galaxy formation. At this stage, the massive neutrinos are at their time sinked by the barionic galactic growing (gravitational) potential, and they finally fill up an extended hot dark galactic halo, *i.e.*, a HDM halo. We apply a simple adiabatic approximation to evaluate the present neutrino number density in those halos (Fargion et al. 1995, 1996). Therefore, the final neutrino number density in the galactic halo n_{ν_r} is enhanced by a factor $\rho_{GB} / \rho_B \sim 10^5 \div 10^7$, where ρ_{GB} and ρ_B label respectively the present barionic mass density in inhomogeneous galaxies and in average cosmic media. In the present work we assume $n_{\nu_r} = 10^{7 \div 9} \text{ cm}^{-3}$. The two order of magnitude of uncertainty window is related to our ignorance of the exact cosmic barion density and galactic (luminous and dark) mass density, as well as to the neutrino barion

clustering efficiency. The consequent extended neutrino halo, related to the combined free-streaming length and characteristic Jeans wavelenght of the two fluids (Fargion 1983) is $l_g \simeq 300 \text{ Kpc} \sim 10^{24} \text{ cm}$. The characteristic mass density needed to solve the galactic dark matter problem is $\rho_{oc} \sim 0.3 \text{ GeV cm}^{-3}$ (Fargion et al. 1995). The corresponding allowed mass density for the relic neutrino halo, for the two extreme clustered value we assumed above, is $\rho(r)_{ov} \sim 0.1/(1+(r/a)^2)(m_\nu/10 \text{ eV}) \cdot 10^{0 \div 2} \text{ GeV cm}^{-3}$ where $a \sim 10 \text{ Kpc}$ well within the critical value ρ_{oc} .

3. Neutrino-neutrino interaction

Now, let us examine the processes that can occur in the interaction of the UHE neutrino with the relic one (see also Roulet 1993). The two main channels involve a W^\pm or a Z^0 exchange via the reactions $\nu_\mu \nu_{\tau_r} \rightarrow \mu \tau$ and $\nu_\mu \nu_{\mu_r} \rightarrow \text{hadrons}$, respectively. For a $\nu \nu_r$ interaction mediated in the t -channel by the W exchange, the asymptotic cross section reaches a plateau of nearly constant value when $s \rightarrow \infty$. On the other hand, for a $\nu \nu_r$ interaction mediated in the s -channel by the Z exchange, a peculiar peak in the cross section occurs due to the resonant Z production at $s = M_Z^2$. However, this occurs for a very narrow and fine-tuned window of energy, and a neutrino mass $m_\nu \sim 4 \text{ eV} (E_\nu/10^{21} \text{ eV})^{-1}$. This resonance for massive light cosmological neutrinos is analogous to the well known one in $\nu_e e^- \rightarrow W^-$ (Glashow 1960; Berezinsky, Gazirov 1977). Here, we just notice this possibility, but we do not assume the lucky coincidence. The exact cross section for the $\nu_\mu \bar{\nu}_{\tau_r}$ (and charge conjugated $\bar{\nu}_\mu \nu_{\tau_r}$) interaction via a W exchange in the t -channel, neglecting the neutrino masses, is

$$\sigma_W(s) = \sigma_{asym} \frac{A(s)}{s} \left\{ 1 + \frac{M_W^2}{s} \left[2 - \frac{s + B(s)}{A(s)} \ln \left(\frac{B(s) + A(s)}{B(s) - A(s)} \right) \right] \right\} \quad (1)$$

where \sqrt{s} is the center of mass energy, the functions $A(s)$, $B(s)$ are defined as

$$A(s) = \sqrt{[s - (m_\tau + m_\mu)^2][s - (m_\tau - m_\mu)^2]} \quad ; \quad B(s) = s + 2M_W^2 - m_\tau^2 \quad (2)$$

and

$$\sigma_{asym} = \frac{\pi\alpha^2}{2\sin^4\theta_W M_W^2} \simeq 108.5 \text{ pb} \quad (3)$$

where α is the fine structure constant and θ_W the Weinberg angle. σ_{asym} is the asymptotic behaviour of the cross section in the ultrarelativistic limit

$$s \simeq 2E_\nu m_\nu = 2 \cdot 10^{23} (E_\nu/10^{22} \text{ eV}) (m_\nu/10 \text{ eV}) \text{ eV}^2 \gg M_W^2 \quad . \quad (4)$$

On the other hand, the interaction of neutrinos of the same flavour can occur via a Z exchange in the s -channel ($\nu_i \bar{\nu}_{i_r}$ and charge conjugated). The cross section for hadron production in $\nu_i \bar{\nu}_i \rightarrow Z^* \rightarrow \text{hadrons}$ is

$$\sigma_Z(s) = \frac{8\pi s}{M_Z^2} \frac{\Gamma(Z^o \rightarrow \text{invis.})\Gamma(Z^o \rightarrow \text{hadr.})}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2} \quad (5)$$

where $\Gamma(Z^o \rightarrow \text{invis.}) \simeq 0.5 \text{ GeV}$, $\Gamma(Z^o \rightarrow \text{hadr.}) \simeq 1.74 \text{ GeV}$ and $\Gamma_Z \simeq 2.49 \text{ GeV}$ are respectively the experimental Z width into invisible products, the Z width into hadrons and the Z full width (Particle Data Group, 1996). Apart from the narrow Z resonance peak at $\sqrt{s} = M_Z$, the asymptotic behaviour is proportional to $1/s$ for $s \gg M_Z^2$. For energies $\sqrt{s} > 2M_W$, one has to include the additional channel of W pair production, $\nu_i \bar{\nu}_{i_r} \rightarrow W^+ W^-$. The corresponding cross section is (Enquist, Kainulainen, Maalampi 1989)

$$\sigma_{WW}(s) = \sigma_{asym} \frac{\beta_W}{2s} \frac{1}{(s - M_Z^2)} \{4L(s) \cdot C(s) + D(s)\} \quad (6)$$

where $\beta_W = (1 - 4M_W^2/s)^{1/2}$ and the functions $L(s)$, $C(s)$, $D(s)$ are defined as

$$L(s) = \frac{M_W^2}{2\beta_W s} \ln \left(\frac{s + \beta_W s - 2M_W^2}{s - \beta_W s - 2M_W^2} \right)$$

$$C(s) = s^2 + s(2M_W^2 - M_Z^2) + 2M_W^2(M_Z^2 + M_W^2) \quad (7)$$

$$D(s) = \frac{1}{12M_W^2(s - M_Z^2)} \times \\ \times \left[s^2(M_Z^4 - 60M_W^4 - 4M_Z^2M_W^2) + 20M_Z^2M_W^2s(M_Z^2 + 2M_W^2) - 48M_Z^2M_W^4(M_Z^2 + M_W^2) \right].$$

The asymptotic behaviour of this cross section is proportional to $(M_W^2/s) \ln(s/M_W^2)$ for $s \gg M_Z^2$. In fig.1 we show the three cross sections eq.1, eq.5, eq.6 as functions of \sqrt{s} .

EDITOR: PLACE FIGURE 1 HERE.

Of course, in our approach we assume a relic neutrino mass of at least a few eV's. A too light neutrino would hardly cluster in galactic halo. Hence, a suppression factor 1/2 arises in the cross sections since in the non relativistic rest frame of the gravitationally bounded neutrinos the helicity of the particle is undefined. This means that the relic neutrino may be found in either left or right handed polarization states. Consequently, the interaction may be either left-handed, *active*, or right-handed, *sterile*, leading to the above suppression factor. Majorana neutrinos, which we do not consider here, are insensible to such suppression.

Cosmic distances $l_c \simeq H^{-1}c \simeq 10^{28} \text{ cm}$ are transparent to UHE neutrinos even for massive diffused neutrinos (with interaction probability $P_c \simeq \sigma_{\nu\nu_r} n_\nu l_c \sim 10^{-4}$). However, denser extended neutrino halos are a more efficient calorimeter. The interaction probability via W exchange (*t*-channel) is $P_g \simeq \sigma_{\nu\nu_r} n_\nu l_g \sim 10^{-3} \div 10^{-1}$, *i.e.* at least four order of magnitude larger than the corresponding interaction probability of UHE ν 's ($E_\nu \sim 10^{21} \text{ eV}$) in terrestrial atmosphere ($P_a = \sigma_{\nu\nu} n_{atm} l_{atm} \sim 10^{-5}$, Gandhi et al. 1996) with an additional suppression factor ($\sim 10^{-2}$) due to the high altitude where the 320 EeV cosmic ray event took place.

The main reaction chains, from the primary proton down to the final 320 EeV photons or protons, via neutrino-neutrino interactions, are described and summarized in tables 1, 2, 3, 4, 5 respectively for the W^\pm (*t* channel), the Z^o (*s* channel) and the $\nu\bar{\nu} \rightarrow W^+W^-$

channel for pion production and the Z^o channel and the $\nu\bar{\nu} \rightarrow W^+W^-$ channel for proton production. The final photons are mainly π^o decay relics from either the τ^\pm , the Z^o or the W^\pm secondaries born in $\nu\nu_r$ interactions in the galactic halo. The final protons³ are among the secondaries of the Z^o or W^\pm hadronic decay.

4. The chain reactions leading to the final photons

There are at least two main sources of UHE neutrinos: photoproduction of pions by interaction of protons and neutrons on the BBR photons (Longair 1994) and pp scattering (Dar, Laor 1996). The neutrino UHE secondaries, that are able to survive from cosmic distances up to the neutrino galactic halo, are the first born muonic and antimuonic from the π^\pm decay and the secondary born from the subsequent μ^\pm decay.

Let us first consider the three different chains of reactions giving rise to final photons. They refer respectively to the interaction of UHE ν s with relic ν s via W^\pm exchange (t -channel, table 1), Z^o exchange (s -channel, table 2) and $\nu\bar{\nu} \rightarrow W^+W^-$ scattering (table 3).

All the reactions in tables 1,2,3 assume an UHE ν born in photoproduction of pions from primary protons (CR protons) onto BBR photons (through either $p\gamma \rightarrow p + N\pi$ or $p\gamma \rightarrow n + N\pi$, where the pion multiplicity is $N \geq 2$). The primordial proton energy is calibrated according to the final CR photon energy of 320 EeV and the different efficiencies of the chains themselves. In other words, this means that we started with the energy of 320 EeV of the observed particle and we walked back the chain from the end to the beginning according to the chains we have proposed in order to obtain the fundamental

³We remind the reader that a vector boson hadronic decay generates protons as well as antiprotons. For our purposes the two kind of particles are equally suitable and we refer to both of them as protons.

input parameter: the primordial proton energy that obviously depends on the chain. For the W^\pm t -channel (table 1), this initial proton energy is relatively small, and the pions, produced by photoproduction, are therefore few ($\sim 2\pi$). For the Z^o s -channel (table 2), the energy is huge, so the corresponding photoproduced pion number is very large ($\sim 12\pi$). For the W^+W^- production (table 3) the energy is quite high and the number of photoproduced pions is not too small ($\sim 10\pi$)⁴. The probability, multiplicity and secondary energies are easily derived as in tables 1,2 and 3.

The successive pion decay $\pi^\pm \rightarrow \mu^\pm + \nu$ (eq. 2a,2b,2c in tables 1,2,3) and muon decay $\mu^\pm \rightarrow e^\pm \nu_e \nu_\mu$ are the main sources of (muonic) UHE neutrinos. These *blind* neutral particles travel through cosmic distances without interacting, and then reach our (neutrino) galactic halo.

Now, the main reaction differentiating the three possible chains in tables 1,2,3, is the UHE ν scattering onto relic ν s in the hot dark matter halo (eq. 3a,3b,3c in tables 1,2,3). The incoming hitting neutrinos are of muonic nature, while the target relic ones, because of the heavier mass, are preferentially tauonic. Indeed, the gravitational clustering of relic cosmic neutrinos in the HDM halo is more efficient for heavier (and slower) ν_{τ_r} , $\bar{\nu}_{\tau_r}$ (Zel'dovich 1980; Fargion 1983; Fargion et al. 1996). For instance, in analogy to the neutron stars, in an ideal *neutrino star* the degenerated equation for the HDM galactic number density of neutrinos grows as m_ν^3 . As one may easily notice in figure 1, where the different cross sections are plotted, the W^\pm t -channel interaction cross section (table 1, eq.1) reaches an asymptotic plateau, while the Z^o s -channel cross section (table 2, eq.5) exhibits an interesting resonance at $s \sim M_Z^2$ (although, as discussed before, for a very narrow m_ν mass

⁴The π multiplicities have been estimated by assuming the scaling law $N \propto s^{1/4}$ and the fact that the charged pions are 2/3 of the total number.

range), and decreases at higher energies. Also, the W^+W^- production, while of some importance at $E_{cm} \sim 2M_W^2$ (where it is comparable with the W^\pm t -channel), is also falling as $\ln(s)/s$.

The final secondaries of the Z^* , W^\pm and τ^\pm decays are (according to the corresponding multiplicity and probability) source of π^o 's whose final photons may be the observed highest energetic cosmic rays.

We notice that the off-shell Z^* decay channel (table 2, eq.5) produces a large population of π^o secondaries ($\sim 20 - 21\pi^o$)⁵. The W^+W^- channel (table 3, eq.6) leads also to a large number of π^o ($\sim 8\pi^o$)⁶. The most favourable chain, for energetics, is the W^\pm exchange in the t -channel that occurs via the τ^\pm hadronic decay. The three chains with the corresponding primordial energy and total probabilities are summarized in tables 1,2,3 and will be further discussed in the conclusions. Even if we carried on the computations keeping split the two ν_μ branches stemming from the π and μ decays for sake of completeness, now we will refer to the specified chain probability as the sum of the two previous ones.

Let us remark that in the UHE neutrino-neutrino scattering the electron neutrino coming from the μ decay can have an important role⁷. Hence, one could consider the W exchange

⁵The π 's multiplicity has been obtained from the first equation in section 6.2 in (Schmelling 1995) and by assuming that the fraction of charged particle is nearly conserved at energies higher than $\sqrt{s} = M_Z$. Finally, we assumed that all the secondaries get about the same amount of energy from the off-shell Z^* decay.

⁶The π 's multiplicity has been obtained by supposing that the W^\pm hadronic decays are similar to the Z^o ones. The Z^o hadron multiplicities can be found in (Knowles et al. 1996).

⁷Another way to get electronic antineutrino is from the neutron beta decay in flight. These $\bar{\nu}_e$ s are extremely energetic and very good candidate for energy transfer. Unfortunately, the free neutron decay, usually important at UHE energy of the order of $E_n \sim 10^{20}$ eV, becomes less and less competitive at higher Lorentz boost. Indeed, at the energies higher than

interactions $\nu_e \bar{\nu}_r$ (or $\bar{\nu}_e \nu_r$), and in particular $\nu_e \bar{\nu}_{\tau_r}$, $\bar{\nu}_e \nu_{\tau_r}$, as a source of UHE electron secondaries. In principle, such UHE electrons may convert half of their energy into photons by Inverse Compton Scattering (ICS) on BBR. This reaction, being so short-cut, is very efficient in UHE photon production. The ICS in galactic halo, while being dominant up to $E_e \sim m_e^2/(h\nu_{opt}) \sim 2 \cdot 10^{11} \text{ eV}$ over the competitive synchrotron radiation, is no longer ruling at very high energies. Indeed, since for $E_e > m_e^2/(h\nu_{opt})$ the Klein-Nishina cross section decreases linearly with the electron energy, the synchrotron radiation losses (and the corresponding interaction lengths) are larger (smaller) by 6 orders of magnitude than the ICS ones (since synchrotron interaction works at *Thomson* constant regime), for UHE electrons whose energy is $E_e \gg m_e^2/(h\nu_{BBR}) \sim 4 \cdot 10^{14} \text{ eV}$, and in particular for $E_e \sim 10^{21} \text{ eV}$. Therefore, we must expect only an associated parassite electromagnetic shower at the characteristic synchrotron radiation energy $E_\gamma \simeq 1.6 \cdot 10^{16} \text{ eV}$ $(E_e/10^{21} \text{ eV})^2$ at lower but significant flux of energy with respect to the UHECR, even in the same direction, but at delayed time. Moreover, because of these synchrotron radiation losses, the interaction length for synchrotron radiation, for the electrons inside our galaxy ($B_G \sim 3 \cdot 10^{-6} \text{ G}$), is reduced to $\lambda_e \simeq 120 \text{ pc}$. Therefore, the probability that such an electron is the progenitor of the observed signal at the Fly's Eye detector is negligible. In particular, this probability

10²¹ eV we are interested here, the neutron mean-free-path is nearly an order of magnitude larger than the corresponding interaction length for neutrons with the 2.73 K BBR in the photoproduction of pions. We just remind these $\bar{\nu}_e$ s from neutron decay because, even if quite rare, they require a primordial proton energy lower than the proposed channels. Indeed, the main artery for the UHE neutrino production is the photopion multiproduction by protons: $p\gamma_{BBR} \rightarrow p + N\pi$, $p\gamma_{BBR} \rightarrow n + N\pi$ with $N \geq 2$. The neutron, being itself a proton secondary, will begin its chain with a degraded energy and, then, with a less favourable rate for the π^\pm production.

is $P_e \simeq \sigma_{\nu\nu_r} n_{\nu_r} \lambda_e \eta_n \sim 3 \cdot 10^{-8}$ where $\eta_n \sim (10^{20} \text{ eV}/E_n)$ is the efficiency for beta-decay. A more interesting probability is obtained if we consider the electrons coming via the t -channel from the tau decay. In this case we get $P_\tau \sim 10^{-5}$, where now $\lambda_e \simeq l_g$, and $E_p \sim 2.2 \cdot 10^{22} \text{ eV}$ for the initial proton energy.

5. The chain reactions leading to the final protons

We now consider the reactions giving rise to final protons. This analysis has a particular importance because local effects could disfavour a shower initiated by a 320 EeV photon. In fact, the interaction between the UHE photon and the virtual photons of the stationary geomagnetic field leads to an electromagnetic cascade whose maximum is not in agreement with the observed data of the Fly's Eye event (Burdman, Halzen, Gandhi, 1997).

So, let us examine the steps leading to the final protons and summarized in tables 4,5. The first three processes in the two chains are the same as for the final photon production. The photoproduction of pions creates charged pions whose decay generates UHE neutrinos able to reach the galactic halo filled up with relic ν s. Now, the $\nu\nu$ interactions either occur via a Z^* exchange (table 4) or can create a W^+W^- pair (table 5). Both the Z^* and the W can then undergo a subsequent hadronic decay (table 5). In the first case, at the relevant Z^* center of mass energy, one gets an average of 2 protons in each hadronic final state, while from the on-shell W hadronic decay one expects on average just one proton. As in the previous section, we derive the corresponding probability and initial proton energy. The main difference with respect to the similar photon channels (table 1,2,3) is the lack of a t -channel because of the absence of τ decays into protons. We also note the more promising role of the W^+W^- channel over the Z^o one.

Let us now compare the results for the photon and proton chains. The Z channel for photons has a better probability but requires an higher initial energy than the analogous

one for protons. These differences are related to the fact that the protons are less abundant than the pions, that, moreover, must still decay into photons. So, the pions need an higher center of mass energy, but the consequent depletion of the cross section is balanced by the larger multiplicity. A similar behaviour can be found in the W^+W^- channel for photons and protons. The difference in the initial energy is just the factor two that stems from the pion decay into photons, while the difference in the probability is related again to the different multiplicity.

As we further discuss in the conclusions, the W^+W^- channel into protons could indeed give a solution to the 320 EeV event. The necessary initial proton energy ($\sim 7.3 \cdot 10^{23}$) is quite high, but the probability ($\geq 1.2 \cdot 10^{-3}$) is at least 120 times more favourable than the one required for the direct travel of a proton from the source to the Earth. Moreover, and most important, such a complicated sequence of reactions explains the embarrassing absence of the expected hundreds of cosmic ray signals at EeV energies that must be present for a direct proton propagation.

6. Conclusions

As summarized in tables 1,2,3 for the final photons, and in tables 4,5 for the final protons, the probabilities and primordial energies for proton and neutron chains for the W , Z and WW channels, are able to give an extragalactic solutions to the UHE puzzle. The neutrinos can be the *ambassadors* of cosmic energetic sources whose energies are finally converted by the relic, massive neutrino halo *calorimeter* into UHE photons or protons. The approximate lower bound on the total probability and the needed initial proton energy, for the different channels, and for a relic neutrino mass $m_\nu \sim 10$ eV, are

table 1 (γ) :	$P_{tot}^W \geq 10^{-3}$	$E_p^W \simeq 4.4 \cdot 10^{22} \text{ eV}$
table 2 (γ) :	$P_{tot}^Z \geq 6.2 \cdot 10^{-3} \left(\frac{m_\nu}{10 \text{ eV}} \right)^{-1}$	$E_p^Z \simeq 3 \cdot 10^{24} \text{ eV}$
table 3 (γ) :	$P_{tot}^{WW} \geq 2 \cdot 10^{-2} \left(\frac{m_\nu}{10 \text{ eV}} \right)^{-1}$	$E_p^{WW} \simeq 1.8 \cdot 10^{24} \text{ eV}$
table 4 (p) :	$P_{tot}^Z \geq 5.1 \cdot 10^{-4} \left(\frac{m_\nu}{10 \text{ eV}} \right)^{-1}$	$E_p^Z \simeq 10^{24} \text{ eV}$
table 5 (p) :	$P_{tot}^{WW} \geq 1.2 \cdot 10^{-3} \left(\frac{m_\nu}{10 \text{ eV}} \right)^{-1}$	$E_p^{WW} \simeq 7.3 \cdot 10^{23} \text{ eV}$

We indicated just the main neutrino mass dependence in the four last probabilities, while the exact one is a more complicated function. This analysis shows that the W^\pm channel for photons and the W^+W^- channel for protons give the most reasonable combination of the total probability and initial proton energy. These probability values are at least three order of magnitude above the corresponding ones for a *direct* neutrino interaction on the terrestrial atmosphere. The required primordial sources may be safely located at any cosmic distance escaping the GZK cutoff. The Seyfert galaxy MCG 8-11-11, which is very close to the arrival direction of the 320 EeV shower and located at a redshift $z=0.0205$ ($D \simeq 70 \text{ Mpc } H_{100}^{-1}$), could be a very natural candidate. Its large observed luminosity in low-energy gamma ($L_\gamma \sim 7 \cdot 10^{46} \text{ erg s}^{-1}$) is of the order of magnitude needed to explain the UHE energetics within our present scheme. Indeed, the total energy needed for any (spherical) source at a distance D to give rise to the 320 EeV event in our approach is: $E_s = (E_p \cdot 4\pi D^2) / (A \cdot P)$, where A is the Fly's Eye detector area [$\sim (30 \text{ Km})^2$] and P is the probability of any given channel. The corresponding power a source needs to get a rate of just one event a year, for the W, Z and WW channels, respectively, and for the most

conservative value of the $\nu\nu$ interaction probability, is

$$\begin{aligned}
 \text{table 1 } (\gamma) : \quad & \dot{E}_s^W \sim 2.2 \cdot 10^{47} (D/100 \text{ Mpc})^2 \text{ erg s}^{-1} \\
 \text{table 2 } (\gamma) : \quad & \dot{E}_s^Z \sim 2 \cdot 10^{48} (D/100 \text{ Mpc})^2 \text{ erg s}^{-1} \\
 \text{table 3 } (\gamma) : \quad & \dot{E}_s^{WW} \sim 3.7 \cdot 10^{47} (D/100 \text{ Mpc})^2 \text{ erg s}^{-1} \\
 \text{table 4 } (p) : \quad & \dot{E}_s^Z \sim 8.1 \cdot 10^{48} (D/100 \text{ Mpc})^2 \text{ erg s}^{-1} \\
 \text{table 5 } (p) : \quad & \dot{E}_s^{WW} \sim 2.5 \cdot 10^{48} (D/100 \text{ Mpc})^2 \text{ erg s}^{-1}
 \end{aligned}$$

These values may be one or two order of magnitude overestimated, if the relic neutrino clustering is more efficient. Anyway, they are already comparable to the MeV observed power from MCG 8-11-11. The energetic and directionality *resonance* toward this source and the quite natural hypothesis that at least a (tau) neutrino mass falls in the range of a few tens eV, as expected in HCDM standard cosmological model, seem to favour our solution of the UHECR puzzle. Nevertheless, we believe that more theoretical and experimental investigations are needed, that may lead to more convincing evidences of an extended dark neutrino halo, and possibly even to an indirect estimate of the neutrino mass.

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Fig. 1.— The total cross sections for the indicated processes as function of the center of mass energy (for a relic neutrino mass $m_\nu = 10\text{eV}$)

Tables caption:— The five tables summarize on each column respectively: the kind of reaction, the corresponding probability, the consequent averaged multiplicity of the final products, the secondary averaged energy. To give an example we refer to table 1 but the same explanation is valid for the other tables also. Reaction 1a) shows the photopion production of primary protons of energy E_p onto BBR photons either for a final p or n creation plus a couple of π . The corresponding probability of pion production is practically the unity for the cosmic distances we assumed here. The charged pions are 2/3 of the total number so we considered a conservative value of 1. Finally, the secondary pion escaping from this reaction has an average energy of 1/3 of the primordial proton energy.

In the reactions 2a), 2'a) we showed the splitting of the chain into two branches due to the generation of UHE neutrinos from the charged pions decay and from the secondary muons decay.

In the reactions 3a), 3a') we considered the ultrahigh neutrino interaction onto the relic cosmic neutrino via the cross section of eq.1 and with the relic neutrino number density discussed in the text. The probability takes into account the value of the cross section at the center of mass energy here involved for the two neutrinos.

In the reaction 4a), 4a') the probability shown refers to the hadronic decay of the tau and as a consequence the final pion multiplicity is just 1.

At the end of the whole chain we calculated the global probability required for the process, for both branches, as a product of the multiplicity and the probability that we derived at each step. The initial needed proton energy E_p is then derived from the chain requiring that at least one of the two branches could give a photon with the known energy of 320 EeV for the final particle.

The further tables 2,3,4,5 must be read in the same way.

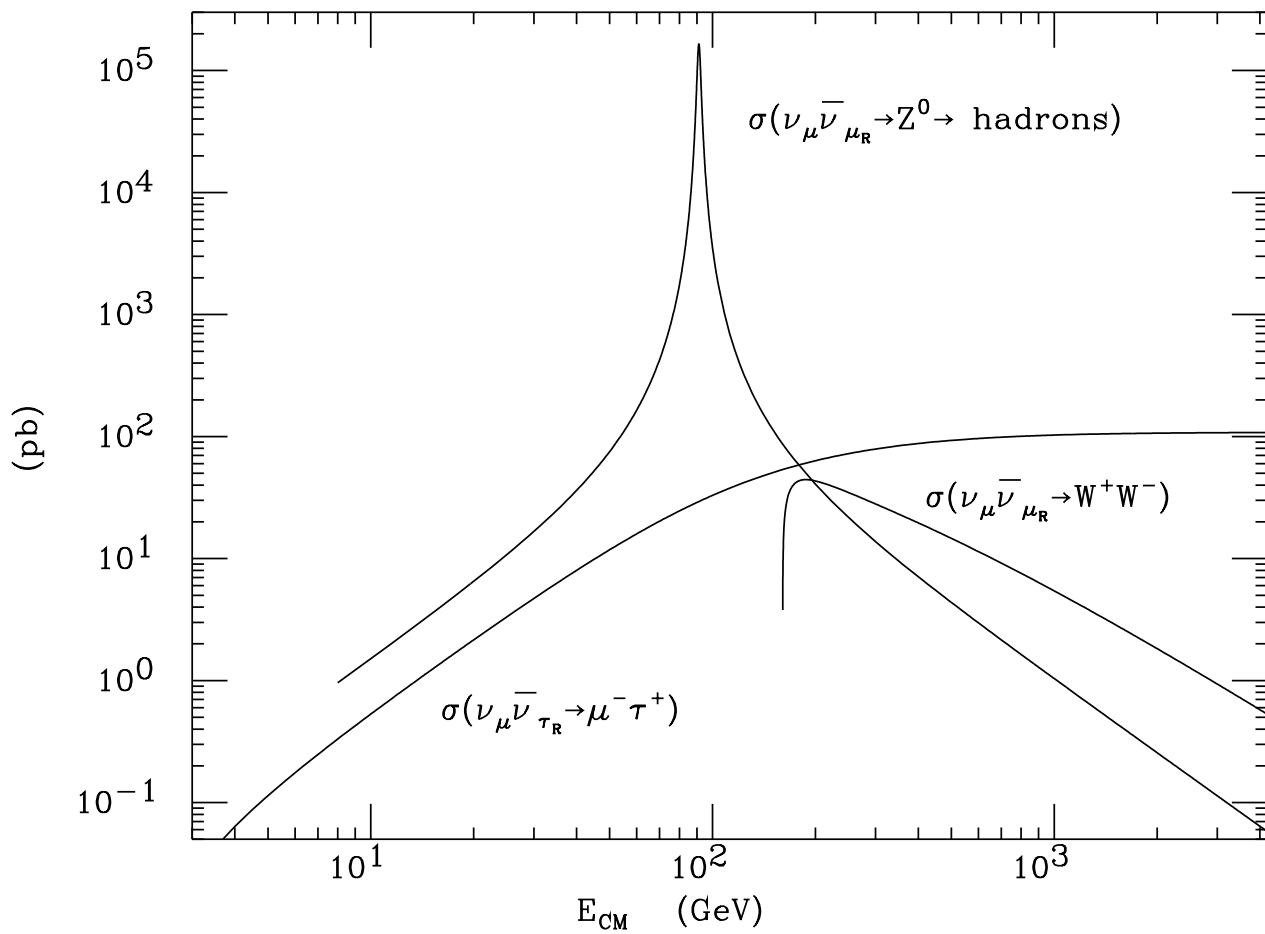


TABLE 1

MAIN W^\pm CHANNEL REACTIONS CHAINS (t -CHANNEL) FOR FINAL PHOTON PRODUCTION

Reaction	Probability	Multiplicity	Secondary energy
1a)			
$p + \gamma \rightarrow (p, n) + 2\pi$	$P_{1a} \simeq 1$	$M_{1a} = 1^a$	$E_\pi \sim \frac{E_p}{3}$
2a)			
$\pi^+ \rightarrow \mu^+ + \nu_\mu$	$P_{2a} \simeq 1$	$M_{2a} = 1$	$E_\nu \sim 0.21E_\pi = 7 \cdot 10^{-2}E_p$
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$			
2a')			
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$	$P_{2a'} \simeq 1$	$M_{2a'} = 1$	$E_\nu \sim \frac{E_\mu}{3} = 0.26E_\pi = 8.8 \cdot 10^{-2}E_p$
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$			
3a)			
$\nu_\mu + \bar{\nu}_{\tau r} \rightarrow \mu^- + \tau^+$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\tau} n_{\nu r} l_g \sim 7.5 \cdot 10^{-4 \div -2}$	$M_{3a} = 1$	$E_\tau \sim \frac{E_{\nu_\mu}}{2} = 3.5 \cdot 10^{-2}E_p$
$\bar{\nu}_\mu + \nu_{\tau r} \rightarrow \mu^+ + \tau^-$			
3a')			
$\nu_\mu + \bar{\nu}_{\tau r} \rightarrow \mu^- + \tau^+$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\tau} n_{\nu r} l_g \sim 8 \cdot 10^{-4 \div -2}$	$M_{3a} = 1$	$E_\tau \sim \frac{E_{\nu_\mu}}{2} = 4.39 \cdot 10^{-2}E_p$
$\bar{\nu}_\mu + \nu_{\tau r} \rightarrow \mu^+ + \tau^-$			
4a)			
$\tau^+ \rightarrow \pi^o + \bar{\nu}_\tau + X$	$P_{4a} \sim 0.37$	$M_{4a} = 1$	$E_{\pi^o} \sim \frac{E_\tau}{3} = 1.2 \cdot 10^{-2}E_p$
$\tau^- \rightarrow \pi^o + \nu_\tau + X$			
4a')			
$\tau^+ \rightarrow \pi^o + \bar{\nu}_\tau + X$	$P_{4a'} \sim 0.37$	$M_{4a'} = 1$	$E_{\pi^o} \sim \frac{E_\tau}{3} = 1.46 \cdot 10^{-2}E_p$
$\tau^- \rightarrow \pi^o + \nu_\tau + X$			
5a)			
$\pi^o \rightarrow \gamma + \gamma$	$P_{5a} \sim 1$	$M_{5a} = 2$	$E_\gamma \sim \frac{E_{\pi^o}}{2} = 5.85 \cdot 10^{-3}E_p$
5a')			
$\pi^o \rightarrow \gamma + \gamma$	$P_{5a'} \sim 1$	$M_{5a'} = 2$	$E_\gamma \sim \frac{E_{\pi^o}}{2} = 7.3 \cdot 10^{-3}E_p$
finally: eq.(1a)	${}^a P_{tot}^W = \Pi_i M_i P_i \sim 5 \cdot 10^{-4 \div -2}$ ${}^{a'} P_{tot}^W = \Pi_i M_i P_i \sim 5.9 \cdot 10^{-4 \div -2}$		$E_p^W \sim 4.4 \cdot 10^{22} \text{ eV}$

Additional W channels if there are neutrino $\nu_\tau \leftrightarrow \nu_\mu$ oscillations:

3'a)

$$\begin{aligned} \bar{\nu}_\tau + \nu_{\tau r} &\rightarrow \tau^- + \tau^+ \\ \nu_\tau + \bar{\nu}_{\tau r} &\rightarrow \tau^+ + \tau^- \end{aligned}$$

^aThis multiplicity refers only to charged pions^bIn calculating the probability for the $\nu\nu$ interaction we assumed: $n_{\nu R} = 10^{7 \div 9} \text{ cm}^{-3}$, $l_g \sim 10^{24} \text{ cm}$. The $\sigma_{\nu_\mu \bar{\nu}_\tau}$ value has been obtained from the corresponding cross section and center of mass energy in fig.1

TABLE 2
MAIN Z CHANNEL REACTIONS CHAINS (*s*-CHANNEL) FOR FINAL PHOTON PRODUCTION

Reaction	Probability	Multiplicity	Secondary energy
1b)			
$p + \gamma \rightarrow (p, n) + 12\pi$	$P_{1b} \simeq 1$	$M_{1b} = 6^a$	$E_\pi \sim \frac{E_p}{13}$
2b)			
$\pi^+ \rightarrow \mu^+ + \nu_\mu$	$P_{2b} \simeq 1$	$M_{2b} = 1$	$E_\nu \sim 0.21E_\pi = 1.6 \cdot 10^{-2}E_p$
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$			
2b')			
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$	$P_{2b'} \simeq 1$	$M_{2b'} = 1$	$E_\nu \sim 0.26E_\pi = 2 \cdot 10^{-2}E_p$
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$			
3b)			
$\nu_\mu + \bar{\nu}_{\mu r} \rightarrow Z^* \rightarrow 20\pi^o + X$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu r} l_g \sim 10^{-5 \div -3}$		
$\bar{\nu}_\mu + \nu_{\mu r} \rightarrow Z^* \rightarrow 20\pi^o + X$	$P_{3b} \simeq 1$	$M_{3b} = 20$	$E_{\pi^o} \sim \frac{E_{\nu_\mu}}{92} = 1.74 \cdot 10^{-4}E_p$
3b')			
$\nu_\mu + \bar{\nu}_{\mu r} \rightarrow Z^* \rightarrow 21\pi^o + X$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu r} l_g \sim 9 \cdot 10^{-6 \div -4}$		
$\bar{\nu}_\mu + \nu_{\mu r} \rightarrow Z^* \rightarrow 21\pi^o + X$	$P_{3b'} \simeq 1$	$M_{3b'} = 21$	$E_{\pi^o} \sim \frac{E_{\nu_\mu}}{95} = 2.1 \cdot 10^{-4}E_p$
4b)			
$\pi^o \rightarrow \gamma + \gamma$	$P_{4b} \simeq 1$	$M_{4b} = 2$	$E_\gamma \sim \frac{E_{\pi^o}}{2} = 8.7 \cdot 10^5 E_p$
4b')			
$\pi^o \rightarrow \gamma + \gamma$	$P_{4b'} \simeq 1$	$M_{4b'} = 2$	$E_\gamma \sim \frac{E_{\pi^o}}{2} = 1.05 \cdot 10^4$
finally: eq.(1b)	${}^b P_{tot}^Z = \Pi_i M_i P_i \sim 3.2 \cdot 10^{-3 \div -1}$ ${}^{b'} P_{tot}^Z = \Pi_i M_i P_i \sim 3 \cdot 10^{-3 \div -1}$		$E_p^Z \sim 3 \cdot 10^{24} \text{ eV}$
<u>Additional reactions not included in the present analysis:</u>			
Z channels if there is neutrino flavor mixing $\nu_\mu \leftrightarrow \nu_\tau$			
3'b)			
$\bar{\nu}_\tau + \nu_{\tau r} \rightarrow 20\pi^o + X$			
$\nu_\tau + \bar{\nu}_{\tau r} \rightarrow 20\pi^o + X$			
Z channel whose efficiency is however suppressed by lower $\nu_e, \bar{\nu}_e$ energies and $n_{\nu_e}, n_{\bar{\nu}_e}$ densities			
3"b)			
$\bar{\nu}_e + \nu_{e r} \rightarrow 20\pi^o + X$			

^aThis multiplicity refers only to charged pions

^bIn calculating the probability for the $\nu\nu$ interaction we assumed: $n_{\nu r} = 10^{7 \div 9} \text{ cm}^{-3}$, $l_g \sim 10^{24} \text{ cm}$. The $\sigma_{\nu_\mu \bar{\nu}_\mu}$ value has been obtained from the corresponding cross section and center of mass energy in fig.1

TABLE 3
MAIN W^+W^- CHANNEL REACTIONS CHAINS FOR FINAL PHOTON PRODUCTION

Reaction	Probability	Multiplicity	Secondary energy
1c)			
$p + \gamma \rightarrow (p, n) + 10\pi$	$P_{1c} \simeq 1$	$M_{1c} = 7^a$	$E_\pi \sim \frac{E_p}{11}$
2c)			
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$	$P_{2c} \simeq 1$	$M_{2c} = 1$	$E_\nu \sim 0.21E_\pi = 1.9 \cdot 10^{-2}E_p$
2c')			
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$	$P_{2c'} \simeq 1$	$M_{2c'} = 1$	$E_\nu \sim 0.26E_\pi = 2.3 \cdot 10^{-2}E_p$
3c)			
$\nu_\mu + \bar{\nu}_{\mu r} \rightarrow W^+ + W^-$ $\bar{\nu}_\mu + \nu_{\mu r} \rightarrow W^+ + W^-$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu r} l_g \sim 7 \cdot 10^{-5 \div -3}$	$M_{3c} = 2$	$E_W \sim \frac{E_{\nu_\mu}}{2} = 9.5 \cdot 10^{-3}E_p$
3c')			
$\nu_\mu + \bar{\nu}_{\mu r} \rightarrow W^+ + W^-$ $\bar{\nu}_\mu + \nu_{\mu r} \rightarrow W^+ + W^-$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu r} l_g \sim 6 \cdot 10^{-5 \div -3}$	$M_{3c'} = 2$	$E_W \sim \frac{E_{\nu_\mu}}{2} = 1.2 \cdot 10^{-2}E_p$
4c)			
$W^\pm \rightarrow 8\pi^o + X$	$P_{4c} \sim 0.7$	$M_{4c} = 8$	$E_{\pi^o} \sim \frac{E_W}{33} = 2.9 \cdot 10^{-4}E_p$
4c')			
$W^\pm \rightarrow 8\pi^o + X$	$P_{4c'} \sim 0.7$	$M_{4c'} = 8$	$E_{\pi^o} \sim \frac{E_W}{33} = 3.6 \cdot 10^{-4}E_p$
5c)			
$\pi^o \rightarrow \gamma + \gamma$	$P_{5c} \simeq 1$	$M_{5c} = 2$	$E_\gamma \sim \frac{E_{\pi^o}}{2} = 1.45 \cdot 10^4E_p$
5c')			
$\pi^o \rightarrow \gamma + \gamma$	$P_{5c'} \simeq 1$	$M_{5c'} = 2$	$E_\gamma \sim \frac{E_{\pi^o}}{2} = 1.8 \cdot 10^4E_p$
finally: eq.(1c)	${}^c P_{tot}^{WW} = \Pi_i M_i P_i \sim 1.1 \cdot 10^{-2 \div 0}$ ${}^{c'} P_{tot}^{WW} = \Pi_i M_i P_i \sim 9.4 \cdot 10^{-3 \div -1}$		$E_p^{WW} \sim 1.8 \cdot 10^{24} \text{ eV}$
Additional reactions not included in the present analysis:			
W^+W^- channels if there is neutrino flavor mixing $\nu_\mu \leftrightarrow \nu_\tau$			
3'c)			
$\bar{\nu}_\tau + \nu_{\tau r} \rightarrow W^+ + W^-$ $\nu_\tau + \bar{\nu}_{\tau r} \rightarrow W^+ + W^-$			
W^+W^- channel whose efficiency is however suppressed by lower $\nu_e, \bar{\nu}_e$ energies and $n_{\nu_e}, n_{\bar{\nu}_e}$ densities			
3''c)			
$\bar{\nu}_e + \nu_{e r} \rightarrow W^+ + W^-$			

^aThis multiplicity refers only to charged pions

^bIn calculating the probability for the $\nu\nu$ interaction we assumed: $n_{\nu r} = 10^{7 \div 9} \text{ cm}^{-3}$, $l_g \sim 10^{24} \text{ cm}$. The $\sigma_{\nu_\mu \bar{\nu}_\mu}$ value has been obtained from the corresponding cross section and center of mass energy in fig.1

TABLE 4
MAIN Z CHANNEL REACTIONS CHAINS FOR FINAL PROTON PRODUCTION

Reaction	Probability	Multiplicity	Secondary energy
1d)			
$p + \gamma \rightarrow (p, n) + 9\pi$	$P_{1d} \simeq 1$	$M_{1d} = 6^a$	$E_\pi \sim \frac{E_p}{10}$
2d)			
$\pi^+ \rightarrow \mu^+ + \nu_\mu$	$P_{2d} \simeq 1$	$M_{2d} = 1$	$E_\nu \sim 0.21E_\pi = 2.1 \cdot 10^{-2}E_p$
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$			
2d')			
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$	$P_{2d'} \simeq 1$	$M_{2d'} = 1$	$E_\nu \sim 0.26E_\pi = 2.6 \cdot 10^{-2}E_p$
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$			
3d)			
$\nu_\mu + \bar{\nu}_{\mu r} \rightarrow Z^* \rightarrow 2p + X$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 2.5 \cdot 10^{-5 \div -3}$		
$\bar{\nu}_\mu + \nu_{\mu r} \rightarrow Z^* \rightarrow 2p + X$		$M_{3d} = 2$	$E_p \sim \frac{E_{\nu_\mu}}{80} \sim 2.6 \cdot 10^{-4}E_p$
3d')			
$\nu_\mu + \bar{\nu}_{\mu r} \rightarrow Z^* \rightarrow 2p + X$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 1.8 \cdot 10^{-5 \div -3}$		
$\bar{\nu}_\mu + \nu_{\mu r} \rightarrow Z^* \rightarrow 2p + X$		$M_{3d'} = 2$	$E_p \sim \frac{E_{\nu_\mu}}{83} \sim 3.15 \cdot 10^{-4}E_p$
finally: eq.(1d)	$d P_{tot}^Z = \Pi_i M_i P_i \sim 3 \cdot 10^{-4 \div -2}$		$E_p^Z \sim 10^{24} \text{ eV}$
	$d' P_{tot}^Z = \Pi_i M_i P_i \sim 2.16 \cdot 10^{-4 \div -2}$		

Additional reactions not included in the present analysis:

Z channels if there is neutrino flavor mixing $\nu_\mu \leftrightarrow \nu_\tau$

3'd)

$$\begin{aligned} \bar{\nu}_\tau + \nu_{\tau r} &\rightarrow Z^* \rightarrow 2p + X \\ \nu_\tau + \bar{\nu}_{\tau r} &\rightarrow Z^* \rightarrow 2p + X \end{aligned}$$

Z channel whose efficiency is however suppressed by lower $\nu_e, \bar{\nu}_e$ energies and $n_{\nu_e}, n_{\bar{\nu}_e}$ densities

3" d)

$$\bar{\nu}_e + \nu_{er} \rightarrow Z^* \rightarrow 2p + X$$

^aThis multiplicity refers only to charged pions

^bIn calculating the probability for the $\nu\nu$ interaction we assumed: $n_{\nu_r} = 10^{7 \div 9} \text{ cm}^{-3}$, $l_g \sim 10^{24} \text{ cm}$. The $\sigma_{\nu_\mu \bar{\nu}_\mu}$ value has been obtained from the corresponding cross section and center of mass energy in fig.1

TABLE 5
MAIN W^+W^- CHANNEL REACTIONS CHAINS FOR FINAL PROTON PRODUCTION

Reaction	Probability	Multiplicity	Secondary energy
1e)			
$p + \gamma \rightarrow (p, n) + 8\pi$	$P_{1e} \simeq 1$	$M_{1e} = 5^a$	$E_\pi \sim \frac{E_p}{9}$
2e)			
$\pi^+ \rightarrow \mu^+ + \nu_\mu$	$P_{2e} \simeq 1$	$M_{2e} = 1$	$E_\nu \sim 0.21E_\pi = 2.3 \cdot 10^{-2}E_p$
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$			
2e')			
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$	$P_{2e'} \simeq 1$	$M_{2e'} = 1$	$E_\nu \sim 0.26E_\pi = 2.8 \cdot 10^{-2}E_p$
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$			
3e)			
$\nu_\mu + \bar{\nu}_{\mu r} \rightarrow W^+ + W^-$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 1.2 \cdot 10^{-4 \div -2}$	$M_{3e} = 2$	$E_W \sim \frac{E_{\nu\mu}}{2} = 1.1 \cdot 10^{-2}E_p$
$\bar{\nu}_\mu + \nu_{\mu r} \rightarrow W^+ + W^-$			
3e')			
$\nu_\mu + \bar{\nu}_{\mu r} \rightarrow W^+ + W^-$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 10^{-4 \div -2}$	$M_{3e'} = 2$	$E_W \sim \frac{E_{\nu\mu}}{2} = 1.4 \cdot 10^{-2}E_p$
$\bar{\nu}_\mu + \nu_{\mu r} \rightarrow W^+ + W^-$			
4e)			
$W^\pm \rightarrow p + X$	$P_{4e} \sim 0.7$	$M_{4e} = 0.8$	$E_p \sim \frac{E_W}{33} = 3.5 \cdot 10^{-4}E_p$
4e')			
$W^\pm \rightarrow p + X$	$P_{4e'} \sim 0.7$	$M_{4e'} = 0.8$	$E_p \sim \frac{E_W}{33} = 4.3 \cdot 10^{-4}E_p$

finally: eq.(1e)

$$\begin{aligned} {}^e P_{tot}^{WW} &= \Pi_i M_i P_i \sim 6.6 \cdot 10^{-4 \div -2} \\ {}^{e'} P_{tot}^{WW} &= \Pi_i M_i P_i \sim 5.6 \cdot 10^{-4 \div -2} \end{aligned}$$

$$E_p^{WW} \sim 7.3 \cdot 10^{23} \text{ eV}$$

Additional reactions not included in the present analysis:

W^+W^- channels if there is neutrino flavor mixing $\nu_\mu \leftrightarrow \nu_\tau$

3'e)

$$\begin{aligned} \bar{\nu}_\tau + \nu_{\tau r} &\rightarrow W^+ + W^- \\ \nu_\tau + \bar{\nu}_{\tau r} &\rightarrow W^+ + W^- \end{aligned}$$

W^+W^- channel whose efficiency is however suppressed by lower $\nu_e, \bar{\nu}_e$ energies and $n_{\nu_e}, n_{\bar{\nu}_e}$ densities

3"e)

$$\bar{\nu}_e + \nu_{e r} \rightarrow W^+ + W^-$$

^aThis multiplicity refers only to charged pions

^bIn calculating the probability for the $\nu\nu$ interaction we assumed: $n_{\nu_r} = 10^{7 \div 9} \text{ cm}^{-3}$, $l_g \sim 10^{24} \text{ cm}$. The $\sigma_{\nu_\mu \bar{\nu}_\tau}$ value has been obtained from the corresponding cross section and center of mass energy in fig.1